Data Assimilation in Shelf Circulation Models

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LONG-TERM GOALS

The goals of this research project are to develop advanced data assimilation (DA) methods for coastal circulation models and to apply these methods to measurements from the Oregon shelf.

OBJECTIVES

The immediate scientific objectives of this research project are to develop practical, but still nearly optimal methods for the assimilation of data into coastal circulation models, and to apply these methods to time-series measurements from moorings and coastally-based high frequency (HF) standard and long range radars, satellite data (SSH, SST), and hydrographic survey data (e.g., from autonomous underwater vehicles, AUVs). An important additional scientific objective is to utilize data assimilation to study the physics of coastal ocean circulation processes.

APPROACH

The proposed research involves a systematic continuation of work in progress that has included assimilation of current measurements from both moored instruments and an array of HF radars deployed along the Oregon coast. The problem of coastal data assimilation has been approached simultaneously from two directions: (i) application of optimal, variational data assimilation schemes to simplified linear models and (ii) application of simplified, sub-optimal data assimilation schemes to a full primitive equation model. Recently, we have begun merging these two approaches, learning about implementation of rigorous variational DA with nonlinear models of coastal ocean dynamics.

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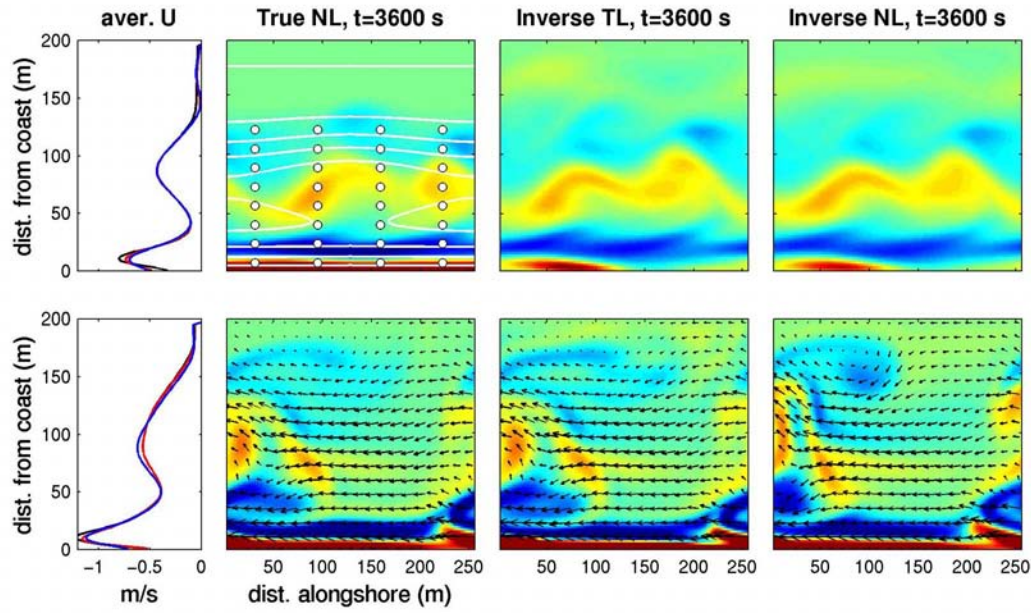| 16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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Figure 1. Our DA system has been tested in an equilibrated wave regime (top plots) and a more strongly nonlinear, irregular regime (bottom plots). In each case, the prior forcing and the prior model state were 0; time-series synthetic data (surface elevation and velocity) were assimilated at the locations shown as circles, in a 1 hour time interval. Linear plots on the left are the time- and alongshore-averaged alongshore current of the true nonlinear solution (black), the inverse tangent linear solution (blue), and inverse nonlinear solution forced by the corrected (inverse) forcing (red). Color maps show snapshots of vorticity (color) and velocity vectors (only in the bottom plots) from those solutions at the end of the assimilation time interval. The nonlinear inverse solution (right) predicts the location of eddies in close correspondence with the truth (second left). White contours are bathymetry (every 0.5 m).

Although the simple linear models cannot represent faithfully all of the detailed physics of the coastal ocean, their relative simplicity has allowed significant insights into the basic nature of the data assimilation problem that cannot be readily inferred from the output of more complete nonlinear models. Our studies of data assimilation in linear models have utilized the variational representer method (RM), and involved both analytical models of shelf dynamics (Scott et al., 2000, Kurapov et al. 1999, 2002) and a numerical model implemented in a study of the M2 internal tide on the mid-Oregon shelf assimilating HF radar surface velocities (Kurapov et al. 2003). These studies proved to be valuable in addressing fundamental questions, such as the extent to which knowledge of surface velocity measurements over a limited area constrains the model solutions at depth or across-shore and alongshore distances from the data sites. Linear models can also be readily utilized to examine the sensitivity of the data assimilation system to errors in data, model parameterizations, wind-stress forcing and boundary conditions (Kurapov et al. 2003). The analysis of linear DA models has facilitated formulation of the statistical error models that are necessary for implementation of systems based on the nonlinear primitive equations and sequential assimilation (Kurapov et al. 2002, 2005a).

Studies using the straightforward, but suboptimal, sequential optimal interpolation (OI) method with the nonlinear primitive equation Princeton Ocean Model (POM) have focused on aspects of modeling the subinertial wind-driven circulation. The POM-OI system was developed and implemented initially

for assimilation of HF radar surface current data (Oke et al. 2002), and then extended to assimilation of velocity measurements from an array of acoustic Doppler profiler (ADP) moorings (Kurapov et al. 2005a,b,c). These studies provided insight into the magnitude and the spatial structure of the dynamical errors, gave us experience working with diverse sets of data (used both for assimilation and solution evaluation), and allowed us to address a number of physical phenomena, including cross-shelf transport and near-bottom mixing variability resulting from flow-topography interactions. The OI data assimilation scheme sequentially updates state variables based on data-model differences and stationary estimates of forecast and data error statistics. Such a simple sequential approach improves modeled coastal ocean circulation on average over the season. However, to improve prediction on the event scale, more elaborate DA methods must be employed.

Merging the two DA approaches mentioned above, we intend to develop methods that are optimal with respect to both choice of a numerical model and data assimilation methodology. In particular, we focus on the development and implementation of the RM with nonlinear high-resolution regional models of coastal ocean dynamics, following methodology outlined by Chua and Bennett (2001). Utilizing nonlinear models, the minimum of the penalty function formulated in RM can be obtained iteratively as a relatively small series of linearized optimization problems (so called "outer loop" iterations). Each linearized problem is solved efficiently in a representer subspace of the state space. Using the indirect representer method (Egbert et al. 1994; also see Chua and Bennett, 2001), the optimum linear combination of the representer solutions can be obtained iteratively in a series of adjoint model and tangent linear model runs ("inner loop" iterations). Thus, large data sets can be assimilated.

Our study has involved testing the RM initially using a shallow water nonlinear model of circulation in the nearshore surf zone. We are also assessing of the utility of the newly available tangent linear (TL) and adjoint (AD) components of the Regional Oceanic Modeling System (ROMS) (Moore et al. 2004, Di Lorenzo et al. 2006), in collaboration with the members of the ROMS Adjoint Group [A. Moore (U. Colorado), H. Arango (Rutgers U.), E. Di Lorenzo (Georgia I. Tech.)]. In addition, in collaboration with A. Bennett and B. Chua (Oregon State U.), we are assessing the utility of, and contributing to, the Inverse Ocean Modeling System (IOM; Chua and Bennett 2001), a computer interface for efficient RM implementation and analysis. In our work on the nearshore shallow water model, we are examining several technical RM-related problems including: assimilation over long time intervals in flows with instabilities; development of computationally efficient optimization algorithms; implementation of effective and dynamically consistent covariance smoothers for initial and open boundary errors; evaluation of approaches for overcoming non-smoothness of open boundary conditions due to logical switching between inflow and outflow conditions, etc. Most of these questions can be explored more easily using our shallow water model, providing guidance for more challenging 3D cases.

Along with development of the DA methodology, Dr. S. Erofeeva, supported by this project, has continued to advance our 3D stratified model for the Oregon shelf flows, testing limited-area versions of ROMS with open boundary conditions suitable for the energetic coastal flows off Oregon and studying possible interactions of wind- and tidally-driven baroclinic flows. Model improvements resulting from those tests will provide better physical compatibility of the assimilated data with the model.
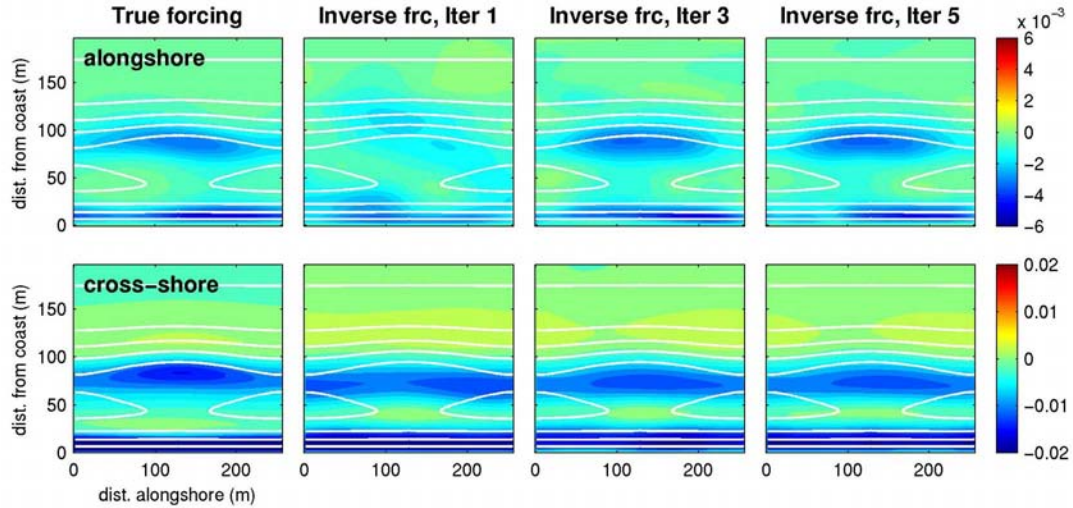
Figure 2. Experiments with synthetic data show that alongshore (top) and cross-shore (bottom) components of the forcing (m2/s2) can be reconstructed by means of data assimilation in a shallow water nearshore model. The prior forcing is 0, and the plots show (left to right): the true forcing and the 1st, 3rd, and 5th outer loop iteration corrected (inverse) forcing fields, for the strongly nonlinear case; time-series synthetic mooring data (see Fig. 1 for locations) are inverted in a 1 hour time interval. White contours are bathymetry (every 0.5 m).

The improvements in the 3D model formulation and advances in the data assimilation methodology will allow us to extend dynamical analysis of coastal flows to a greater range of spatial and temporal scales and to address a number of oceanographic research issues such as: (i) the relative importance of local forcing and open boundary inputs for coastal ocean prediction, (ii) mechanisms responsible for material transport between the coastal and interior ocean, (iii) predictability limits of transient oceanic flows, etc.

WORK COMPLETED

To better understand technical issues associated with TL&AD ROMS, the RM, and IOM, we have developed our own TL and AD codes for the two-dimensional barotropic (shallow-water) nonlinear model. The system can be utilized to find, by means of data inversion, improved time- and space-variable forcing, initial and boundary conditions. Instantaneous or time-averaged observations can be assimilated. These codes have passed stringent tests of adjoint symmetry and have exhibited convergence in dataless ("Picard") iterations. In collaboration with B. Chua, our shallow water codes have been integrated into IOM. Utilizing the indirect representer method, we developed and routinely utilized a preconditioner to accelerate the convergence of inner loop iterations (Egbert 1997). It is based on a limited number of representer solutions computed directly. Preconditioner computations have been done on the parallel computers of the Alaska Research Supercomputer Center. We will soon be able to run these computations locally, using a newly acquired 32-processor Linux cluster, bought partly using funds from this project.

The resulting DA system has been applied to synthetic data assimilation experiments in a problem of alongshore flows over variable beach topography driven by gradients of radiation stresses from breaking waves in the surf zone (Slinn, Allen, and Holman, 2000). In these DA studies, the true

forcing was spatially variable, but time-invariant. Depending on the magnitude of the bottom friction parameter, the alongshore flow may exhibit shear instabilities that result in regular equilibrated wave patterns in a weakly nonlinear regime (Figure 1, top) or irregular "turbulent" behavior in a weakly frictional and strongly nonlinear regime (Figure 1, bottom). In a periodic channel, we have run successful experiments with synthetic data in both regimes. The data were sampled from a "true" fully developed unsteady nonlinear solution that featured an alongshore current in excess of 1 m/s and intensive eddy variability. The prior initial conditions and forcing were 0; hence, all the information about the flow and forcing was extracted from the data. The goal of DA was to obtain improved estimates of both the initial conditions and the forcing (Figure 2) that would, in turn, yield a dynamically balanced nonlinear solution predicting eddies deterministically over much larger time intervals (up to 1 h) than the characteristic time scale of meanders and eddies (5-15 min) or the similar convergence limit time scale found in dataless (Picard) iterations of the tangent linear model.

DA tests in a limited-area shallow water nearshore model with open boundary conditions have been performed for a weakly nonlinear regime and for cases where the prior is relatively close to the true solution. We have experimented with different open boundary formulations, from "clamped" conditions to more rigorous and reliable Riemman-characteristic based conditions (Blayo and Debreu, 2005). More challenging experiments, exploring the open boundary options in a strongly nonlinear regime, are being approached.

In a parallel effort, in preparation for DA in a model with open boundaries, we have experimented with a limited-area model of the Oregon shelf area between 41-47N, based on ROMS (2-km horizontal resolution) and nested in a larger periodic channel model. The model was forced with the time-varying wind stress for summer 2001 and with the barotropic M2 tidal fluxes along the open boundaries, from the data assimilative shallow water tidal model of Egbert and Erofeeva (2002). Aspects of the interactions of wind- and tidally-driven baroclinic shelf flows have been analyzed using both this set-up and a simplified, two-dimensional (2D: variations in the vertical and across-shore, uniformity alongshore) ROMS configurations. In 2D ROMS computations, we forced the model with an alongshore upwelling favorable wind stress on the surface and barotropic M2 tidal flux at the offshore open boundary. The model resolution was 500 m in the horizontal and 60 layers in the vertical. Experiments included a 20-day spin-up run forced with the constant wind stress and a 45-day run forced with wind stress and heat flux using atmospheric measurements off Oregon for summer 2001.

Also, we have nested ROMS (at 3-km horizontal resolution) in a monthly climatology derived from 4 years of output from the NCOM regional model of California Current System (NCOM solutions have been provided by J. Kindle, NRL). In this part, we collaborated with Dr. B.J. Choi (OSU) who has been investigating optimal options for nesting as part of a GLOBEC/NEP project supported by NOAA. The runs in this nested configuration, using climatologic fields, have been performed for April-August 2002 using spatially variable COAMPS wind forcing. The model-data comparisons (using satellite alongtrack altimetry, mooring and HF radar data) are being performed. Sensitivity studies are planned to investigate the relative effect of variable Coriolis parameter and spatially variable wind stress on coastal current separation and cross-shore material transport near Heceta Bank and Cape Blanco.
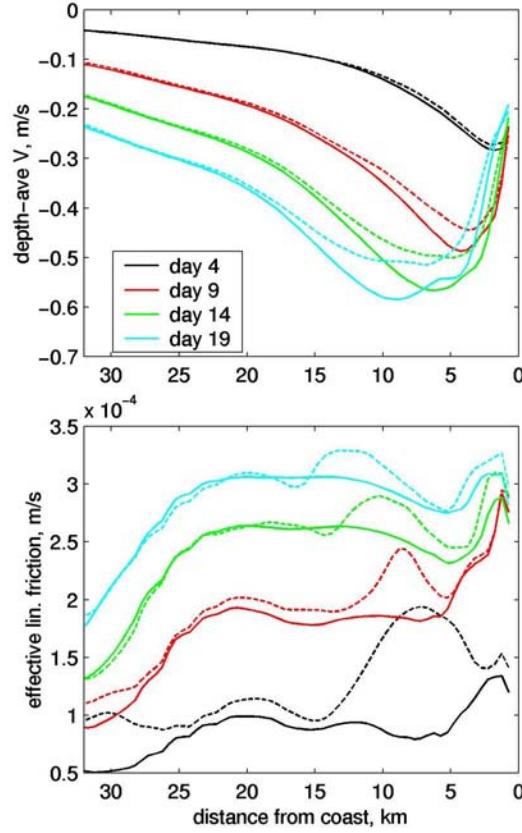
Figure 3. Results from two-dimensional (vertical and cross-shore coordinates) model experiments show that effects of internal tides on the subinertial wind-driven coastal current are: (top) the reduced tidally-averaged, depth-averaged alongshore velocity and (bottom) the increased effective linear bottom friction coefficient. Dashed lines are cases Tide+Wind (TW) and solid lines are Wind Only (WO) cases, days 4, 9, 14, and 19 (spin-up cases applying a constant southward alongshore wind stress of 0.05 N/m2).

RESULTS

In the implementation of our shallow-water DA model, we have learned how to resolve a number of RM-related technical issues that include formulation of appropriate adjoint procedures for the forcing and boundary conditions; tangent linearization of the nonlinear equations maintaining consistency between the continous and discrete model formulations; convergence acceleration using the preconditioner; capabilities to assimilate time-averaged observational information. These findings have been communicated to the ROMS group during joint meetings and workshops.

One challenge of assimilating data in a nonlinear regime is that the flow variability resulting from intrinsic eddy interactions is not directly controlled by the forcing. However, in our studies using the shallow water nearhore DA model, we have found that the eddy variability can be predicted deterministically if the assumed forcing error covariance allows some time variability in the forcing, even though the true forcing is time-independent. This is achieved by implementing a forcing error correlation function separated into the (order one) stationary and (small amplitude) non-stationary parts, allowing forcing fluctuations to be minimized while still providing control on the eddy field.

In a limited area domain with open boundaries, correction of open boundary inputs by means of DA provides an additional opportunity to control (predict deterministically) variability of nonlinear flows. Testing the open boundary version of our system, we verified that using simple "clamped" conditions (specifying all fields at the open boundary) may cause computational instabilities during minimization. The underlying linear mathematical problem with these conditions is overspecified and the intermediate approximations to the open boundary values, as minimization proceeds, are not necessarily dynamically consistent, resulting in shock wave generation at the boundaries. A better option is to use Riemman-characteristic based boundary conditions (Blayo and Debreu, 2005). In the latter case, the type and the number of conditions depends on the strength and direction of the flow through the boundary (these conditions are in general nondifferentiable; general utility of the representer method with these conditions is yet to be investigated).

In a study of interaction of wind- and tidally driven shelf flows, cases forced with tides only (TO), wind stress only (WO), or tides and winds in combination (TW) have been analyzed. Comparisons of solutions WO and TW during the spin-up from rest showed that a 10-15 cm s-1 internal tide can cause a 10 cm s-1 reduction in the intensity of the upwelling jet (Figure 3a). This reduction is accompanied by an increase in the effective linear friction coefficient (Rooth 1972), computed as $C_d = \{\tau_b\}/\{v_b\}$, where τ_b and v_b are the alongshore bottom stress and velocity, correspondingly, and $\{..\}$ denote averaging over a tidal cycle (Figure 3b). Curiously, in the spin-up case the zone of higher C_d is found on the offshore side of the upwelling jet (compare Figure 3a and 3b). In cases forced by the time-variable wind stress, we can see substantial tidal modulations in the level of the turbulent dissipation rate ε in the surface and bottom boundary layers and we also find patches of elevated ε in the middle of the water column associated with combined upwelling- and tidally-related velocity shear (Figure 4).
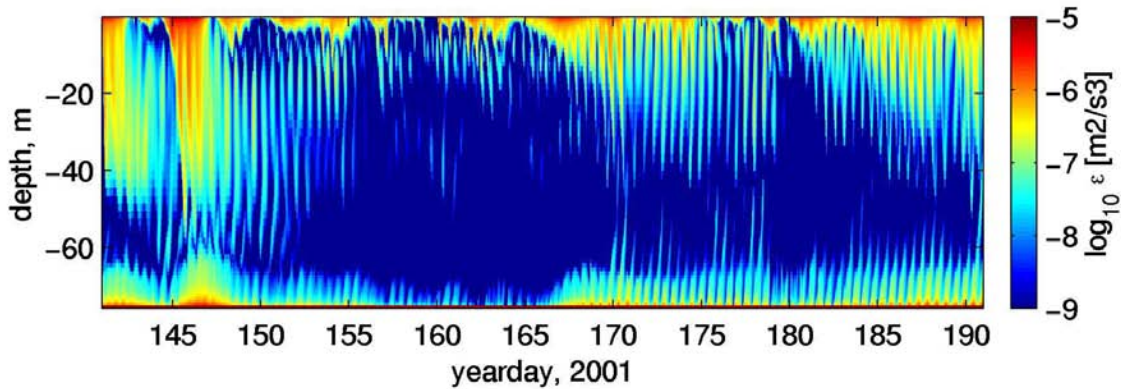

Figure 4. Tidal modulation of the turbulent dissipation rate (contoured as a function of time and depth) in the surface and bottom boundary layers and in the middle of the water column at a mid-shelf location (based on 2D (vertical and cross-shore coordinates) ROMS computation forced with time-variable wind stress and heat flux corresponding to 2001).

In 3D ROMS experiments studying wind and tidally driven flows in combination, we found that the magnitude and the spatial structure of the internal tidal signal on the surface varied significantly, depending on the location of the upwelling front and jet. Preliminary comparisons with mooring data have suggested that inclusion of tidal forcing may improve model variability on subinertial time scales, providing better consistency of the prior model and the data to be assimilated.

IMPACT/APPLICATIONS

Studies with the shallow water model have delivered important information on utility of the variational data assimilation in a nonlinear flow regime, providing guidance for more computationally and dynamically challenging 3D cases. ROMS modeling studies have demonstrated coupling between subinertial wind-driven and superinertial internal tidal motions on the shelf.

TRANSITIONS

Under NOAA funding through the Cooperative Institute for Oceanic Satellite Studies (CIOSS; PIs: R. M. Samelson, G. D. Egbert, A. L. Kurapov), the ROMS based model of wind-driven circulation on the Oregon shelf has been incorporated into a prototype operational coastal ocean system, forced with fields from the mesoscale atmospheric ETA model and providing 3-day forecasts. This new automatic system provides an initial framework, into which future modeling and DA capabilities will be incorporated, as appropriate.

RELATED PROJECTS

The tangent linear and adjoint codes for ROMS (Moore et al., 2004, Di Lorenzo et al. 2006), made available to us recently, have been developed with the support of grants from the Office of Naval Research and National Science Foundation (http://marine.rutgers.edu/po/index.php?page=&model=roms).

Progress on variational data assimilation through this project will directly benefit the research in two projects: (1) "Effects of meso- and basin scale variability on zooplankton populations in the California Current System using data-assimilative, physical/ecosystem models", US-GLOBEC-NEP, NOAA and (2) "Boundary conditions, data assimilation, and predictability in coastal ocean models", ONR-NOPP.

Funds allocated in this project for permanent equipment have been matched by the award from the OSU Research and Equipment Fund resulting in a purchase a 32-processor linux cluster that will be used in this project.

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